Wideband Adaptive RF Protection (WARP)

Enable the use of wideband software defined radios in congested and contested environments

Timothy M. Hancock

February 11, 2020

Agenda

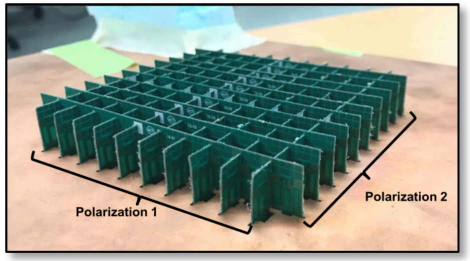
- 0800-0900: Check-In
- 0900-0905: Welcome & Security Introduction
- 0905-0915: Remarks from Dr. Mark Rosker, DARPA MTO Director
- 0915-0935: Contracting with DARPA
- 0935-1010: WARP Overview & Program Structure
- 1010-1030: Networking and Teaming Break
- 1030-1130: Q&A / Discussion
- 1130-1300: Networking and Teaming
- 1300-1700: 1-on-1 Sessions

WARP Program Overview

The Quest for Wideband Software-Defined Radios

Wideband Antennas & Arrays

>10:1 Bandwidth



Tightly Coupled Dipole Array

Archimedean Spiral

Tapered Vivaldi

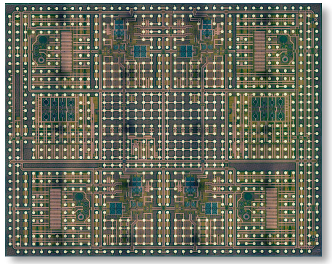
J. Zhong, et al, in *IEEE T-AP*, March 2019.
E. G. Tianang, et al, in IEEE T-AP, Jan. 2018.
A. Ali, et al, 2017 International Symposium on AP.

Why not connect the antenna directly to the radio?

Wideband Receiver Technology

Tuned & RF Sampling to >20 GHz

ACT Common Module



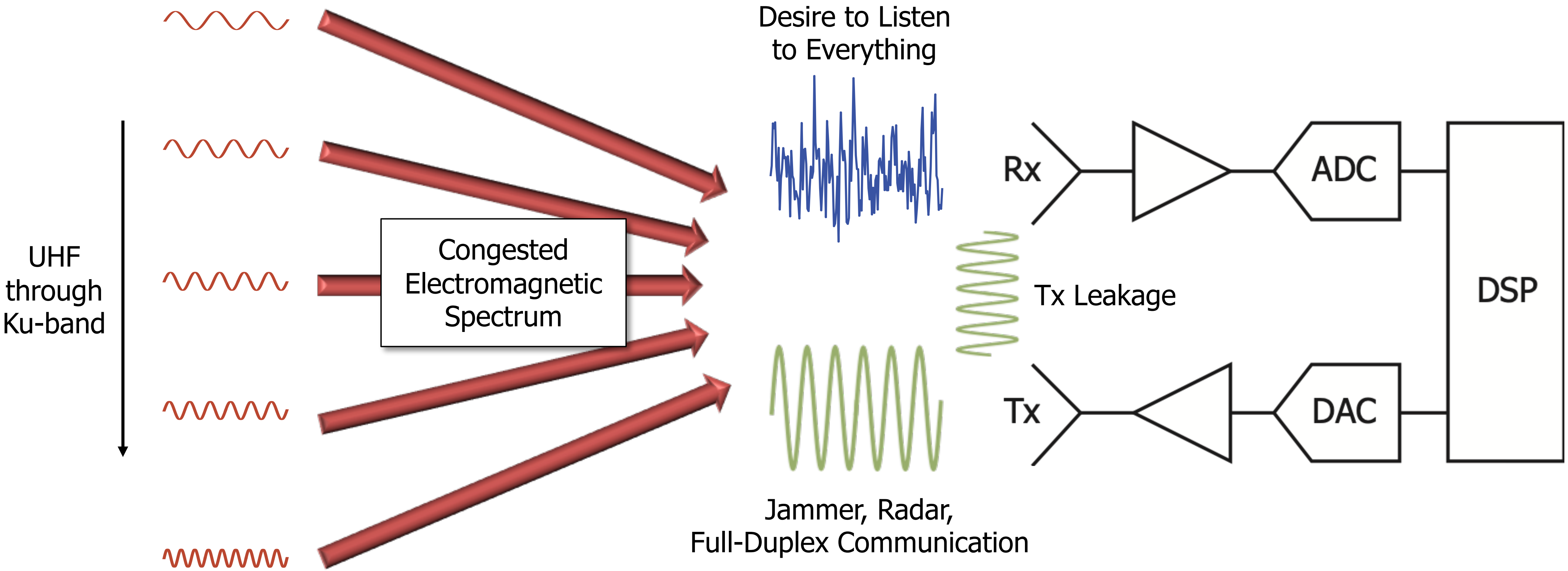
RF-FPGA & Hedgehog MATRICs Chip

COTS 10 GSPs ADC

Northrup Grumman, BAE, & Analog Devices

We have the bandwidth, but lack in dynamic range

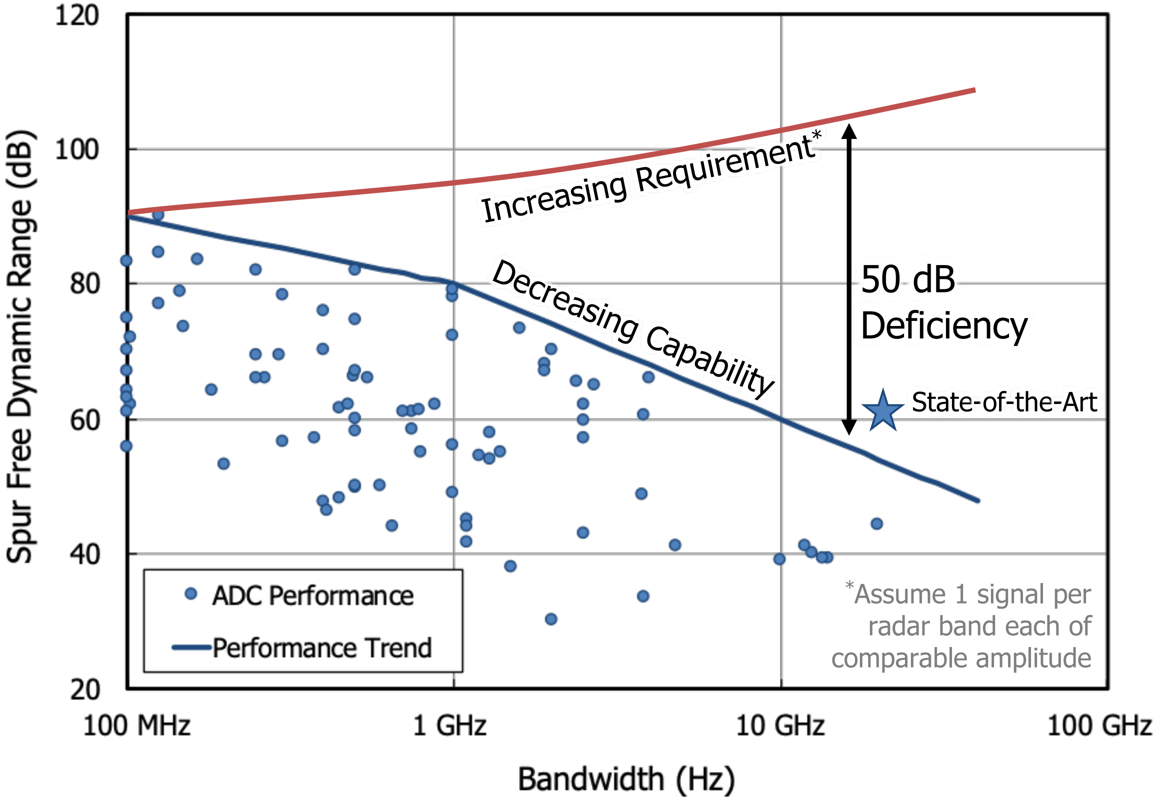
Congested Environment with External & Self-Interference



The large number of signals in a congested environment challenges our dynamic range

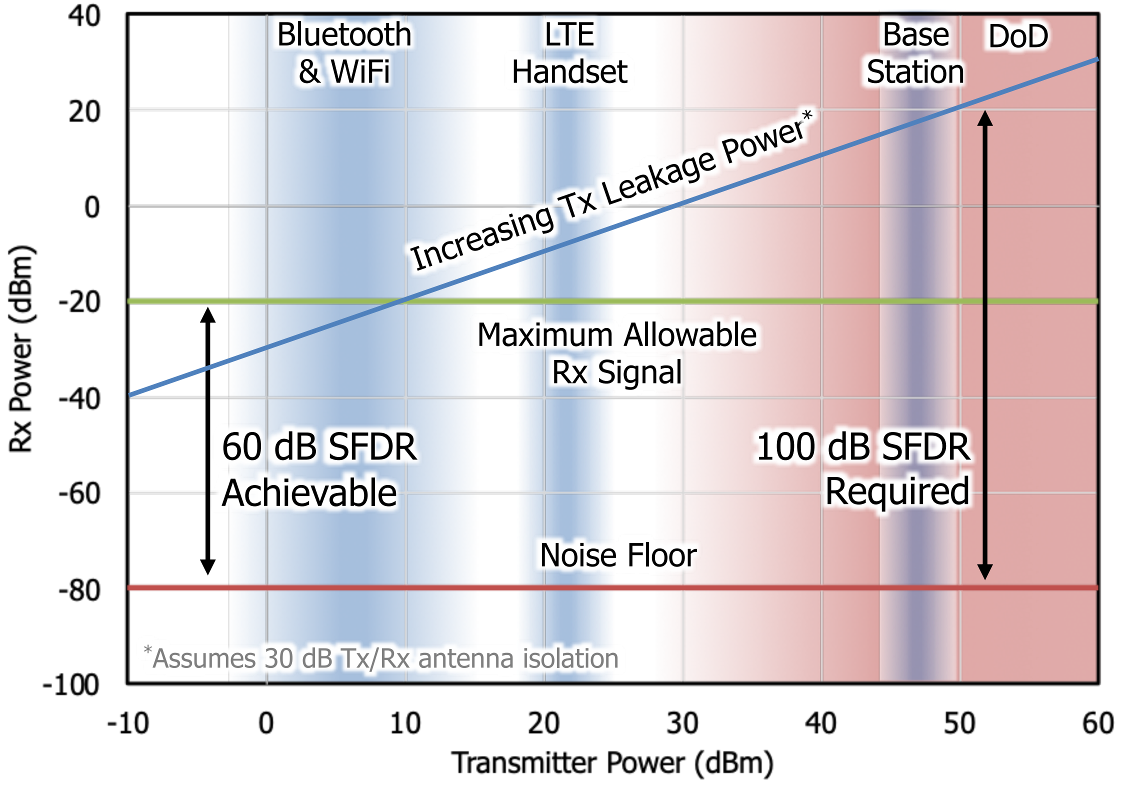
Wideband Receivers Have Insufficient Dynamic Range

Performance Gap with External Interference



Up to 50 dB of performance gap depending on contested spectrum threat scenario

Performance Gap with Self-Interference

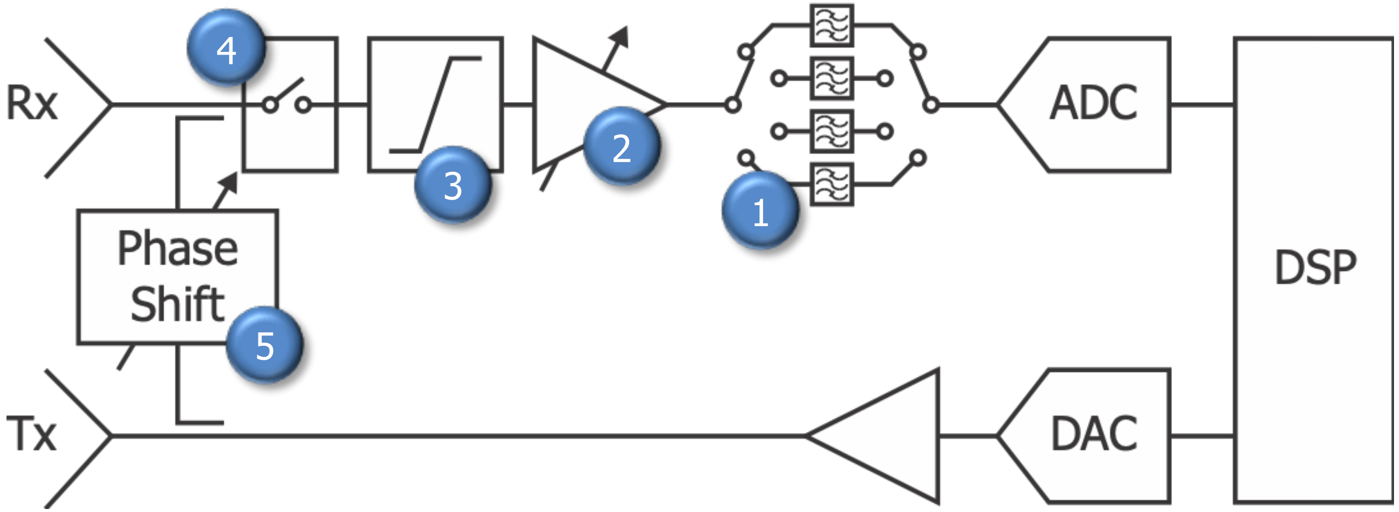


20-40 dB performance gap for any transmit power above 1 Watt

SFDR – Spur Free Dynamic Range
ADC - Analog to Digital Converter

How We Protect Receivers Today

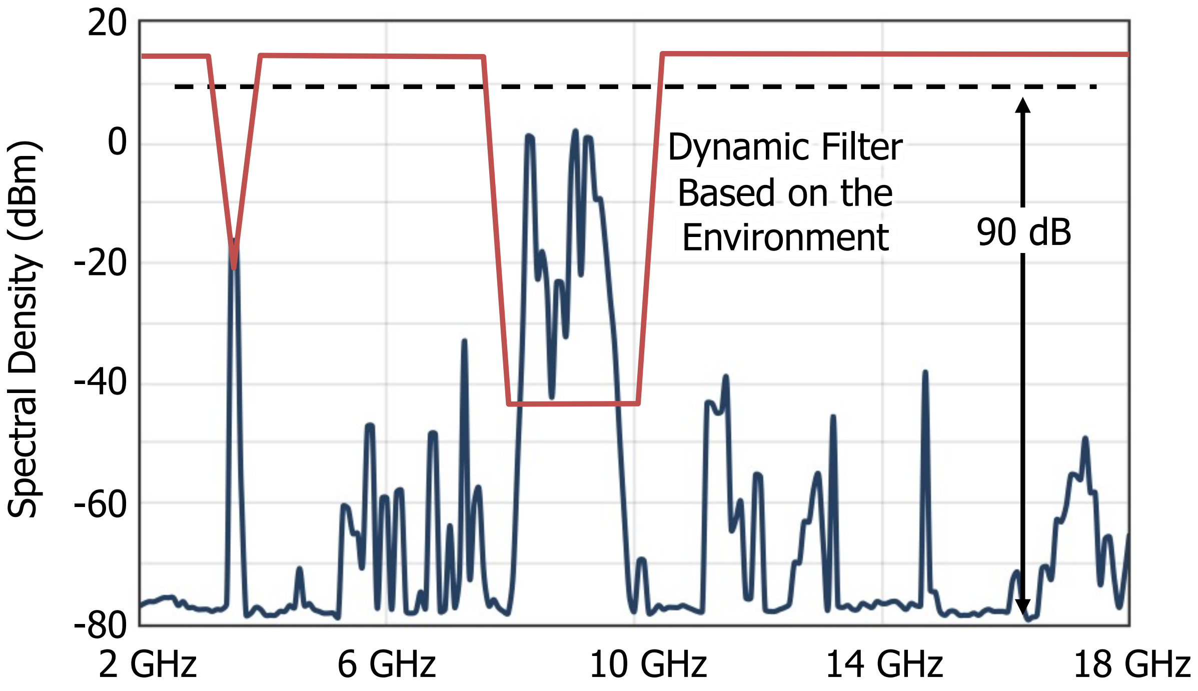
	External Interference Mitigation Techniques	Limitation
1	Pre-planned switched filter bank	Observes only single band, also large and/or lossy
2	Turn down the gain on all signals	Limits sensitivity to small signals
3	Signal limiters, i.e. clipping of large signals	Introduces cross-modulation distortion



	Self-Interference Mitigation Techniques	Limitation
4	Disconnect Rx when Tx is turned on	Can only listen half of the time (half-duplex)
5	Cancel self-interference	Limited to very narrow bandwidths (<50 MHz)

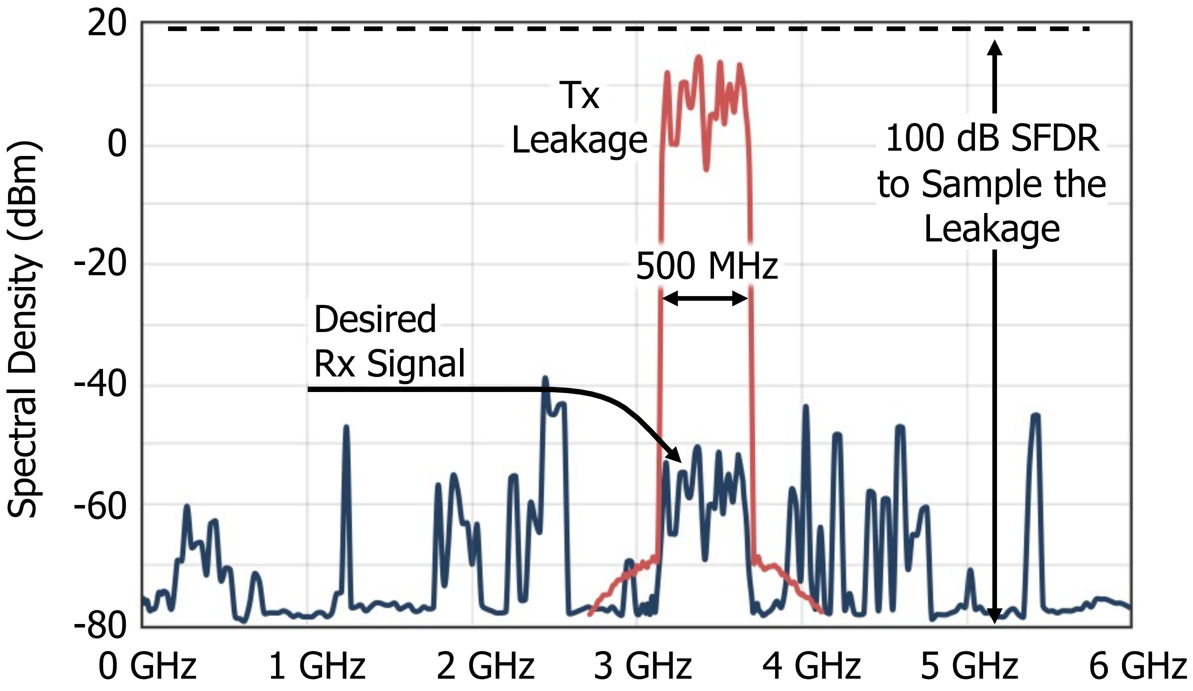
How We Would Like to Protect Receivers in the Future

Wideband Adaptive Filtering



Listen to the environment, adaptively react & selectively attenuate only the large signals

Wideband Signal Cancellation



Estimate the leakage path & adaptively cancel the transmitter leakage

Key Challenges to Wideband Adaptive RF Protection

<u>Wideband Adaptive Filtering</u>

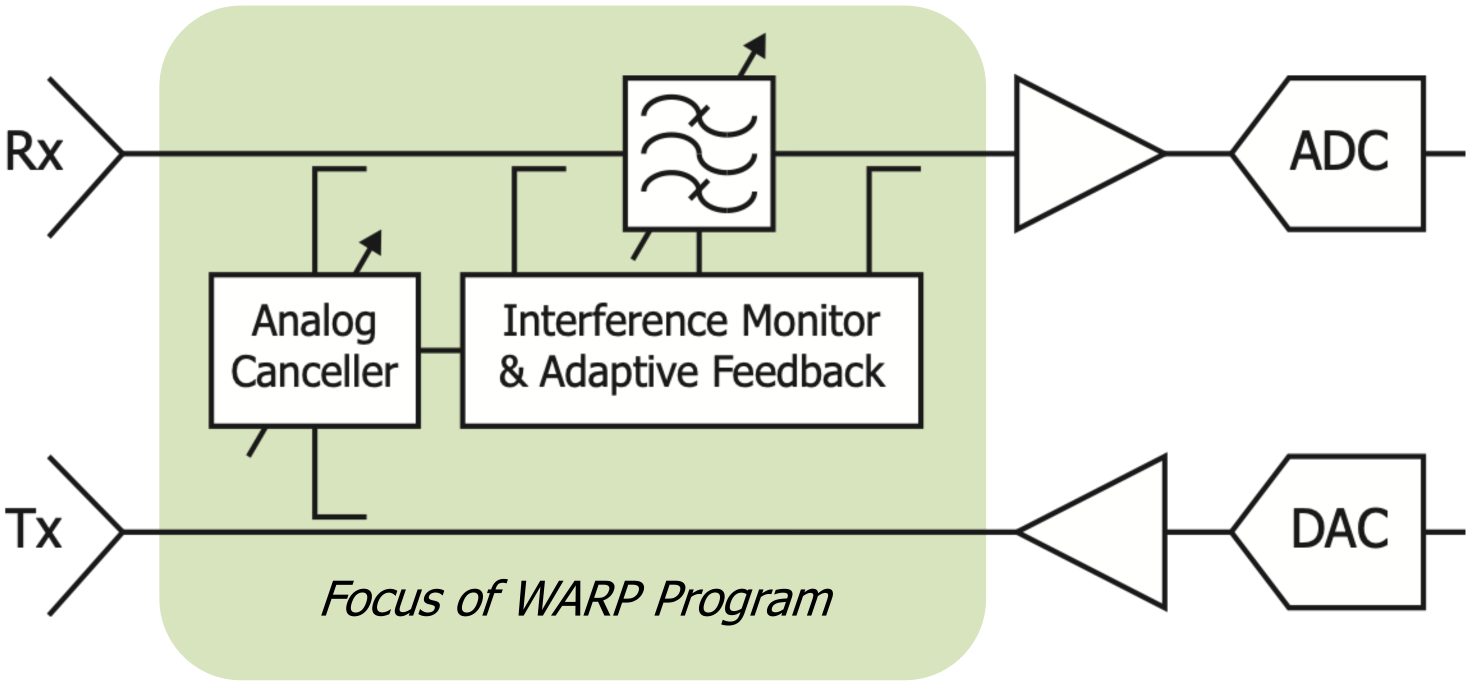
- 2-18 GHz filtering
- Reconfigurable band pass/stop protection

<u>Wideband Signal Cancellation</u>

- 0.1-6 GHz analog cancellers
- Wide bandwidth over large delay spreads

<u>Autonomous Control</u>

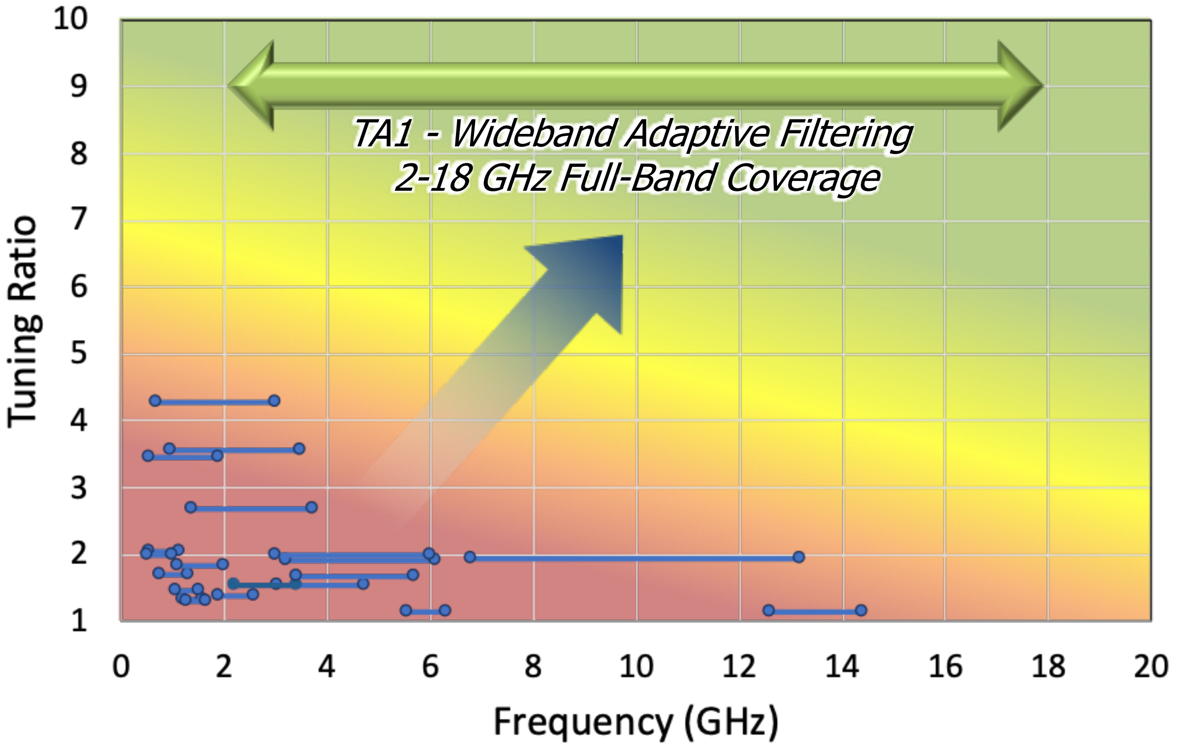
- Monitor external & self-interference
- Implement timely tuning, <100 μs



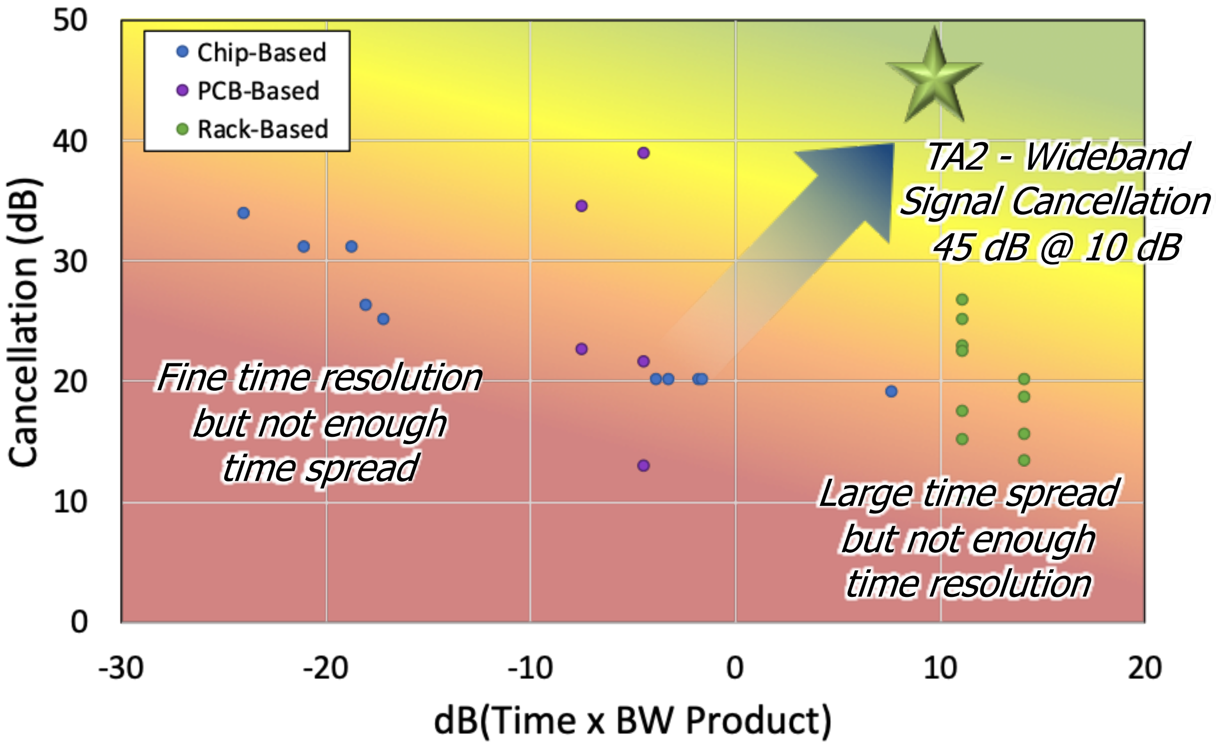
Enable the use of wideband software defined radios in congested and contested environments

What are the Hard Problems?

Tuning Ratio in Published RF Filters



Cancellation in Published RF Cancellers

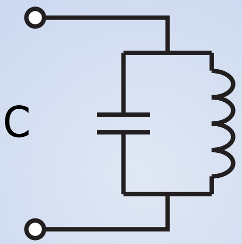


Break the 2:1 tuning limit and scale to >3:1 in the 2-18 GHz band to enable full-band performance

Approach 10 dB time-bandwidth product and maintain fine time resolution for deep cancellation

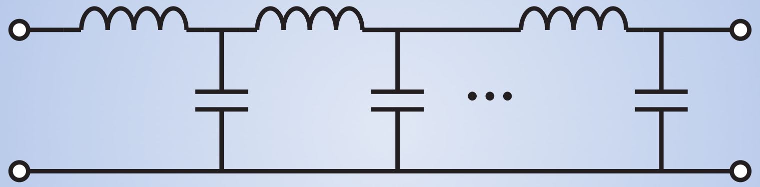
Why is Brute Force Wideband Tuning Difficult?

Resonator: the building block of filters



Resonant Frequency $$f_0 = \frac{1}{2\pi\sqrt{LC}} \text{ Hertz}$$

Delay: the building block of cancellers



Propagation Delay $$\tau_d = \sqrt{L'C'} \text{ seconds/meter}$$

- L is not practical to tune & C is typically limited to about 3:1 in real circuits
- C is inside of a square root function (slowly varying & and compressing function), reducing the achievable frequency/delay tuning to less than 1.7:1

Traditional tuning through capacitive loading alone is fundamentally limited by physics

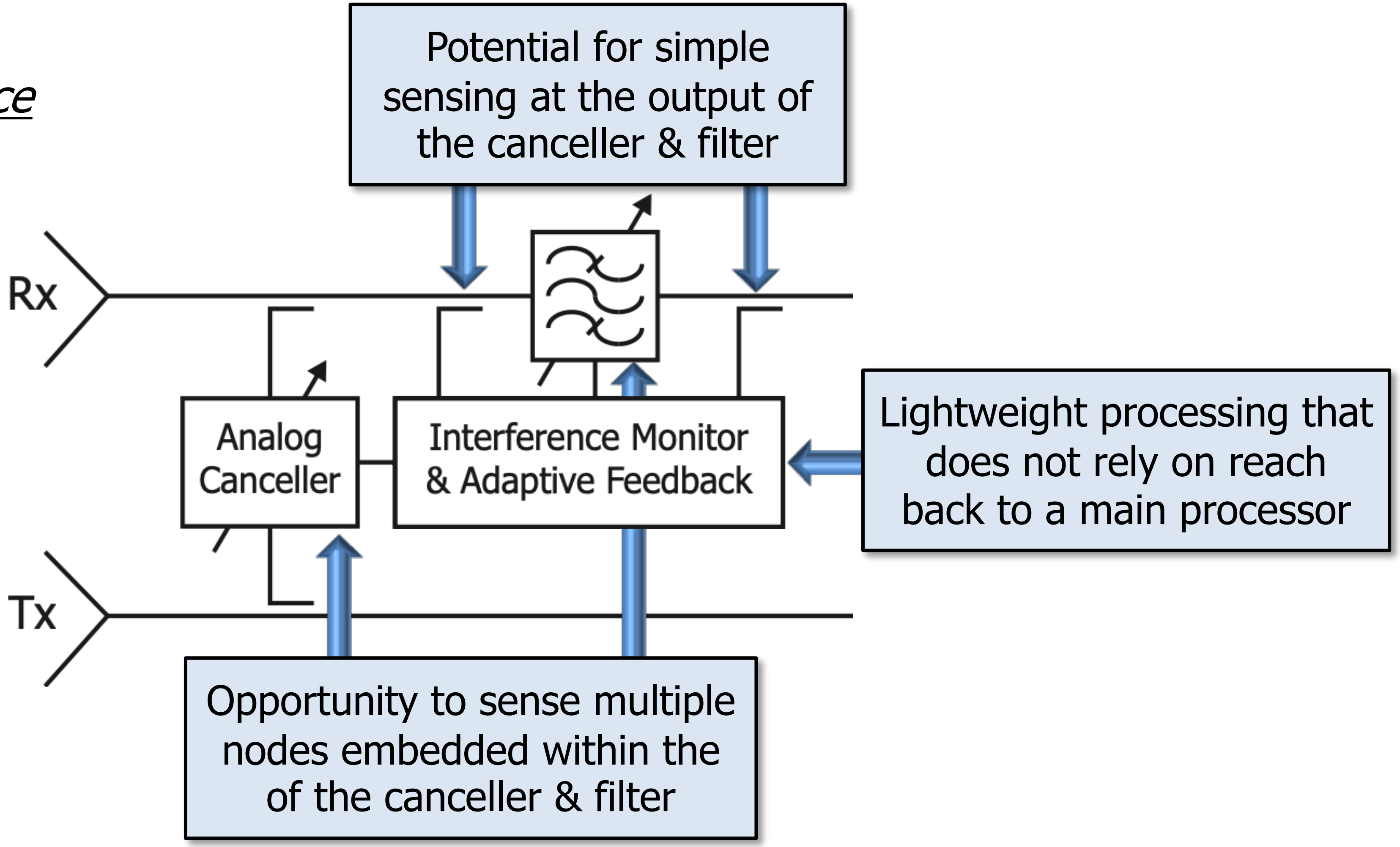
Adaptive Protection – Embedded Sensing & Control

Large & Complex Control Surface

- Number of control inputs could approach 100
- Likely not a monotonic surface

Opportunity

- Embedded sensing in the RF hardware
- Embedded control that mixes *a priori* look-up tables and adaptive algorithms



Key aspects of sensing and control can be embedded into RF hardware

Program Objectives

Program Objectives

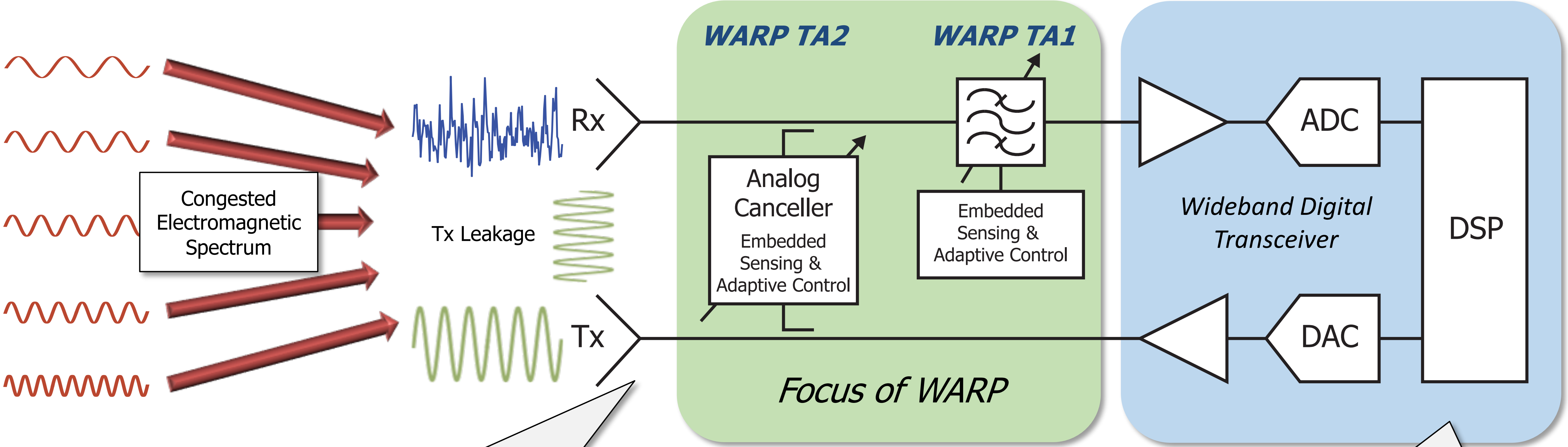
- Break through the **2:1 tuning limit** for RF filters, **scale to 3:1** tuning and ultimately demonstrate **2-18 GHz** tuning coverage
- Achieve **low insertion loss** and **high linearity** for use at the input of wideband receivers
- Break through the **time-bandwidth limitation** of RF canceller circuits
- Achieve **fine time resolution** over **wide delay spread** for wideband cancellation (or the dual version in the frequency domain)
- **Adaptive response** that protects wideband receivers

Expected Areas of Innovation

- Novel filter tunable circuit architectures that **go beyond just adding tunable capacitors** to fixed-frequency designs (transverse architectures, intrinsically switched, analog FIR, etc.)
- Novel **time-delay circuits** (or dual version in the frequency domain), i.e. analog memory, storage, etc.
- **Embedded sensing** to monitor signal levels and/or leakage channels with **adaptive closed-loop control**

WARP Program Structure

What is included in WARP?



WARP is not interested in developing new antenna designs, circulators, electrically balanced duplexers, frequency duplexers, etc. for improved antenna isolation

Both may be brought to bear for demonstrations

WARP is not interested in developing new digital transceivers or DSP for digital cancellation to remove residual leakage

WARP Program Plan

FY 2020 | FY 2021 | FY 2022 | FY 2023 | FY 2024

CY 2020 | CY 2021 | CY 2022 | CY 2023 | CY 2024

Phase 1 – 18 mo. | **Phase 2 – 18 mo.** | **Phase 3 – 12 mo.**

Feb '20	Proposers Day
Mar '20	Abstracts Due
Apr '20	Proposals Due
Sept '20	Program Kickoff
Mar '22	Phase 1 Review
Sep '23	Phase 2 Review
Sep '24	Phase 3 Review

WARP TA1
Wideband Adaptive Filtering

- Phase 1: *2:1 center frequency* — *Demonstrate scalable tuning that does not rely on incremental or brute force approach*
- Phase 2: *3:1 center frequency* — *Scale tuning beyond an octave & implement environment aware, adaptive tuning*
- Phase 3: *2-18 GHz Coverage* — *Full-band demonstration*

WARP TA2
Wideband Signal Cancellation

- Phase 1: *Low-band / high-band cancellation >100 MHz / >400 MHz* — *Demonstrate wideband cancellation with realistically long delay spread as specified*
- Phase 2: *Low-band / high-band cancellation >250 MHz / >1000 MHz* — *Scale performance & implement closed-loop channel estimation & adaptation*
- Phase 3: *0.1-1 GHz and/or 1-6 GHz* — *Full-band demonstration*

TA1 - Wideband Adaptive Filtering

Develop reconfigurable RF filters that adaptively respond to the environment over 2-18 GHz

Metric	Phase 1	Phase 2	Phase 3	Note
Operating band of interest	2-18 GHz	2-18 GHz	2-18 GHz	1
Average Insertion Loss (passive circuits)	<5 dB	<3 dB	<3 dB	2
Average Noise Figure (active circuits)	<8 dB	<6 dB	<6 dB	2
Center frequency tuning ratio	>2:1	>3:1	Demo of full-band solution	3
Bandwidth tuning ratio	>3:1	>5:1	>5:1	4
In-band / Out-of-band IIP3	>15 dBm / >50 dBm	>20 dBm / >60 dBm	>20 dBm / >60 dBm	5,6
Out-of-band rejection	>30 dB	>40 dB	>40 dB	7
Maximum out-of-band input signal	>10 dBm	>20 dBm	>20 dBm	8
Maximum allowable output power	<-20 dBm	<-20 dBm	<-20 dBm	9
Expected in-band input signal	<-20 dBm	<-20 dBm	<-20 dBm	10
Built-in intelligence	Embedded sensing only	Closed-loop adaptivity	Closed-loop adaptivity	11
Reconfiguration speed	–	<100 μs	<100 μs	12
Power consumption	<250 mW	<250 mW	<250 mW	13

Key Decision Metrics

TA1 - Wideband Adaptive Filtering

1. The frequency band in which the filter will operate. Only in Phase 3 will full band coverage be required. See center frequency tuning in note 3.
2. For passive circuits the **average insertion loss** shall be measured over the **-3 dB bandwidth** and shall include any loss due to embedded sensing. If the design has active embedded RF gain, then **noise figure shall be used** as the relevant metric to track the impact on receiver sensitivity.
3. Ratio of the highest to lowest center frequency of the pass/stop band over which the filter is tuned and there shall be **no gaps** over the tuning range.
4. Ratio of the highest to lowest bandwidth of the pass/stop band over which the filter is tuned. For bandpass, the bandwidth is defined as the **-3 dB bandwidth** and for bandstop, the bandwidth is defined by the **out-of-band rejection** metric.
5. The input third-order intercept point (IIP3) measured using two tones in the passband.
6. The input third-order intercept point (IIP3) measured using two tones in the stopband.
7. For both bandpass and bandstop performance, this is the rejection in the stopband and **may be a tunable** parameter between the metric and 0 dB. For bandpass, the **transition bandwidth** from passband to stopband may be **performer defined** based on the chosen resonator quality factor and filter order. For bandstop, the stopband will be self-consistent with the reported bandwidth tuning; see note 4.
8. The **maximum input power** level of a single tone in the stopband.
9. The total output power, in-band and out-of-band, at the output of the filter. This is the expected maximum signal allowed into a typical wideband receiver that would follow the WARP filter and the corresponding peak-to-peak voltage may be considered as the **threshold for protecting the receiver** against distortion.
10. The maximum input power level of a single tone in the passband.
11. In Phase 1, only **embedded sensing** will be implemented and filter control may be implemented off-line (Matlab, Labview, etc.) for characterization of the other metrics. In Phase 2 and 3, a real-time **COTS controller** may be used for closed-loop control, based on the embedded sensing and consistent with the reconfiguration speed metric.
12. Reconfiguration speed is the total delay from an environmental change or other external control stimulus until the observed change in the output of the RF signal. This time is expected to include any **delay in the sensing, computation and hardware control**.
13. Power consumption is the total power required for the filter and any embedded sensing. The **power of any COTs processing** in Phase 2 and Phase 3 is **not included** because power reduction of an FPGA or microcontroller implementation is not a goal of this program and could be optimized in the future on a per application basis.

Point of Security for TA1 - Wideband Adaptive Filtering

Commerce Control List (CCL) Category 3A001b.5

Electronically or magnetically tunable band-pass or band-stop filters, having more than 5 tunable resonators capable of tuning across a 1.5:1 frequency band (f_{max}/f_{min}) in less than 10 μs and having any of the following: b.5.a. A band-pass bandwidth of more than 0.5% of center frequency; or b.5.b. A band-stop bandwidth of less than 0.5% of center frequency.

- While faster is better, the TA1 tuning speed requirement is not the primary focus of the program and it is **unlikely that performers will attempt to exceed the program metric by 10x** to go below the 10 μs threshold, unless it was easily achievable with their chosen technology.
- If at any point in the execution of the WARP program there are simulations or measurements that indicate that the proposed TA1 solution will cross the thresholds outlined in the EAR, this will result in the work **no longer being fundamental research**, if it had previously been deemed as such.
- Non-fundamental research is subject to the Covered Defense Information Controls outlined in Section IV.B.5 of the BAA and the work may become subject to export control. **University performers should be especially aware of this particular EAR CCL category.**

TA2 - Wideband Signal Cancellation

Develop wideband analog signal cancellation to adaptively remove Tx leakage from 0.1-1 GHz & 1-6 GHz

Metric	Phase 1	Phase 2	Phase 3	Note
Operating band of interest	Performer may choose one or both “low-band” (0.1-1 GHz) and/or “high-band” (1-6 GHz)			1
Center frequency tuning	>2:1	>3:1	Demo of full-band solution	2
Low / high-band cancellation bandwidth	>100 MHz / >400 MHz	>250 MHz / >1000 MHz	>250 MHz / >1000 MHz	3
Low / high-band delay spread	>25 ns / >5 ns	>50 ns / >10 ns	>50 ns / 10 ns	4
Tx signal cancellation	>35 dB	>45 dB	>45 dB	5
Coupled power from Tx output	>10 dBm	>20 dBm	>20 dBm	6
Maximum power to cancel at Rx input	>10 dBm	>20 dBm	>20 dBm	7
Residual power after signal cancellation	<-25 dBm	<-25 dBm	<-25 dBm	8
Canceller OIP3	>50 dBm	>60 dBm	>60 dBm	9
Residual noise figure impact	<4 dB	<2 dB	<2 dB	10
Built-in intelligence	Embedded sensing only	Closed-loop adaptivity	Closed-loop adaptivity	11
Reconfiguration speed	–	<100 μs	<100 μs	12
Power consumption	<250 mW	<250 mW	<250 mW	13

Key Decision Metrics

TA2 - Wideband Signal Cancellation

1. Performers must choose to operate either across the low-band (100-1000 MHz) or the high-band (1-6 GHz) or choose both, and this selection must be clearly stated in the proposal.
2. Ratio of the highest to lowest center frequency of the pass/stop band over which the filter is tuned. If digital tuning is implemented, there shall be **no gaps** over the tuning range.
3. The minimum **instantaneous bandwidth** of the canceller.
4. The difference in time between the **longest leakage path** and the **shortest leakage path**.
5. Attenuation of the transmitter self-interference achieved by the RF canceller.
6. The hypothetical RF power coupled from a high-power amplifier. This is the **input power to the RF canceller** and indicates the required power handling of the RF canceller.
7. The maximum RF power that appears at the receiver input due to transmitter self-interference. This is also the effective **RF power** internal to the RF canceller **that will be subtracted** from the canceller receive input.
8. The residual RF power after signal cancellation at the output of the WARP canceller and the input of a wideband digital receiver. This power and the corresponding peak-to-peak voltage may be considered as **the threshold for protecting the receiver** against distortion.
9. Output referenced third-order intercept point (OIP3) of the canceller measured before any signal subtraction (or with no leakage path present). This will indicate the **residual third-order intermodulation** (IM3) products introduced by the canceller and should be measured at the maximum power that is to be cancelled at the Rx input (note 7). For example, in Phase 3, a 20 dBm maximum power, would indicate 2 tones at 14 dBm. With an OIP3 of 60 dBm, this will result in IM3 products at -92 dBc or -78 dBm.
10. The degradation in receive signal-to-noise ratio due to the addition of the canceller. This may include physical loss from the summing junction, but is typically **residual uncancelled noise** introduced by the canceller electronics.
11. In Phase 1, only **embedded sensing** will be implemented and canceller control may be implemented off-line (Matlab, Labview, etc.) for characterization of the other metrics. In Phase 2 and 3, a real-time **COTS controller** may be used for closed-loop control, based on the embedded sensing and consistent with the reconfiguration speed metric.
12. Reconfiguration speed is the total delay from an environmental change or other external control stimulus until the observed change in the output of the RF signal. This time is expected to include any **delay in the sensing, computation and hardware control**.
13. Power consumption is the total power required for the canceller and any embedded sensing. The **power of any COTs processing** in Phase 2 and Phase 3 is **not included** because power reduction of an FPGA or microcontroller implementation is not a goal of this program and could be optimized in the future on a per application basis.

Things to Highlight in your Technical Approach (BAA Section IV.B.2)

TA1 - Wideband Adaptive Filtering

1. State the frequency range within 2-18 GHz that will be chosen for implementation in Phase 1 and Phase 2 along with **rationale for why the ranges were chosen** as a path to achieve full-band, 2-18 GHz coverage by the end of Phase 3.
2. State the absolute bandwidth of the proposed bandpass and/or bandstop filtering and how this relates to **resonator quality factor (Q), chosen filter order** and the stated insertion loss and stopband rejection goals of the program.
3. As part of the adaptive control, state **what will be sensed** (power, voltage, current), where in the circuit it will be sensed and how it will be sensed.
4. State the expected **algorithm approach** and **processing requirements** in Phase 2/3 for closed loop adaptation.
5. State the **testing strategy** in each phase, especially as it pertains to Phase 2/3 where closed-loop adaptation will be implemented.

TA2 - Wideband Signal Cancellation

1. State the frequency range within the low band and/or high band that will be chosen for implementation in Phase 1 and Phase 2 along with **rationale for why the ranges were chosen** as a path to achieve full-band (low band and/or high band) coverage by the end of Phase 3.
2. State the number of **expected time/frequency taps** and how they will be controlled (tuned, switched, etc.) to achieve the required combination of bandwidth, delay spread and cancellation stated in the metrics.
3. As part of the adaptive control, state **what will be sensed** (power, voltage, current), where in the circuit it will be sensed and how it will be sensed.
4. State the expected **algorithm approach** and **processing requirements** in Phase 2/3 for closed loop adaptation.
5. State the **testing strategy** in each phase, especially as it pertains to Phase 2/3 where closed-loop adaptation will be implemented. State whether any wideband antenna isolation measurements will be made to characterize specific leakage channels. State **how the transmit-to-receive leakage path will be emulated** and the type of **leakage channel** that will be used for testing (multipath, amplitude distribution, etc.) and what waveforms will be used to demonstrate the bandwidth of the canceller.

Evaluation Criteria

1. Overall Scientific and Technical Merit

The proposed technical approach is **innovative, feasible, achievable, and complete**. Task descriptions and associated technical elements provided are complete and in a logical sequence with all proposed deliverables clearly defined such that a final outcome that **achieves the goal** can be expected as a result of award. The proposal identifies major technical **risks and planned mitigation** efforts are clearly defined and feasible. The proposed technical team has the **expertise and experience** to accomplish the proposed tasks.

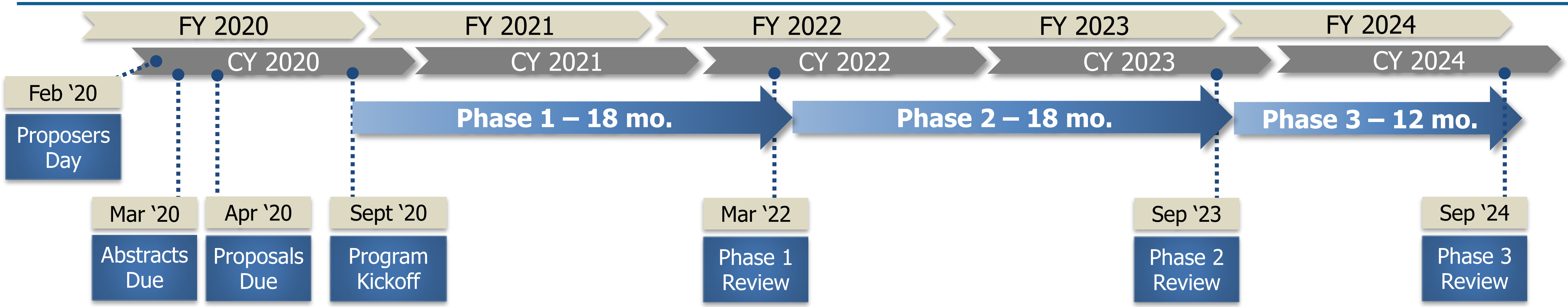
2. Potential Contribution and Relevance to the DARPA Mission

The potential contributions of the proposed effort are **relevant to the national technology base**. Specifically, DARPA's mission is to make pivotal early technology investments that create or prevent strategic surprise for U.S. National Security. The proposer clearly demonstrates its plans and capabilities to contribute to U.S. national security and U.S. technological capabilities. The evaluation will consider the proposer's **plans and capabilities to transition** proposed technologies to U.S. national security applications and to U.S. on-shore industry.

3. Cost Realism

The proposed costs are **realistic** for the technical and management approach and **accurately reflect the technical goals and objectives** of the solicitation. The proposed costs are consistent with the proposer's Statement of Work and reflect a sufficient understanding of the costs and level of effort needed to successfully accomplish the proposed technical approach. The costs for the prime proposer and proposed subawardees are **substantiated by the details** provided in the proposal.

Proposal Timeline



Important Dates

- Abstracts Due: ***March 9, 2020***
- Abstract Feedback: ***Around the end of March***
- FAQ Submission Deadline: ***April 9, 2020***
- Proposal Due Date: ***April 23, 2020***
- Estimated period of performance start: ***September 2020***

BAA Coordinator: **HR001120S0027@darpa.mil**

WARP Question & Answer Session

Frequently Asked Questions

Q: Does DARPA intend to have multiple awards?

A: Yes.

Q: How much funding is available?

A: Approximately **$20M per TA** is expected to be made available, for a **total of $40M**. This is subject to receiving high-quality proposals and may be adjusted up or down accordingly during source selection.

Q: Can my organization respond to both TAs and if so, how?

A: Yes, please submit **separate self-contained proposals** for each TA.

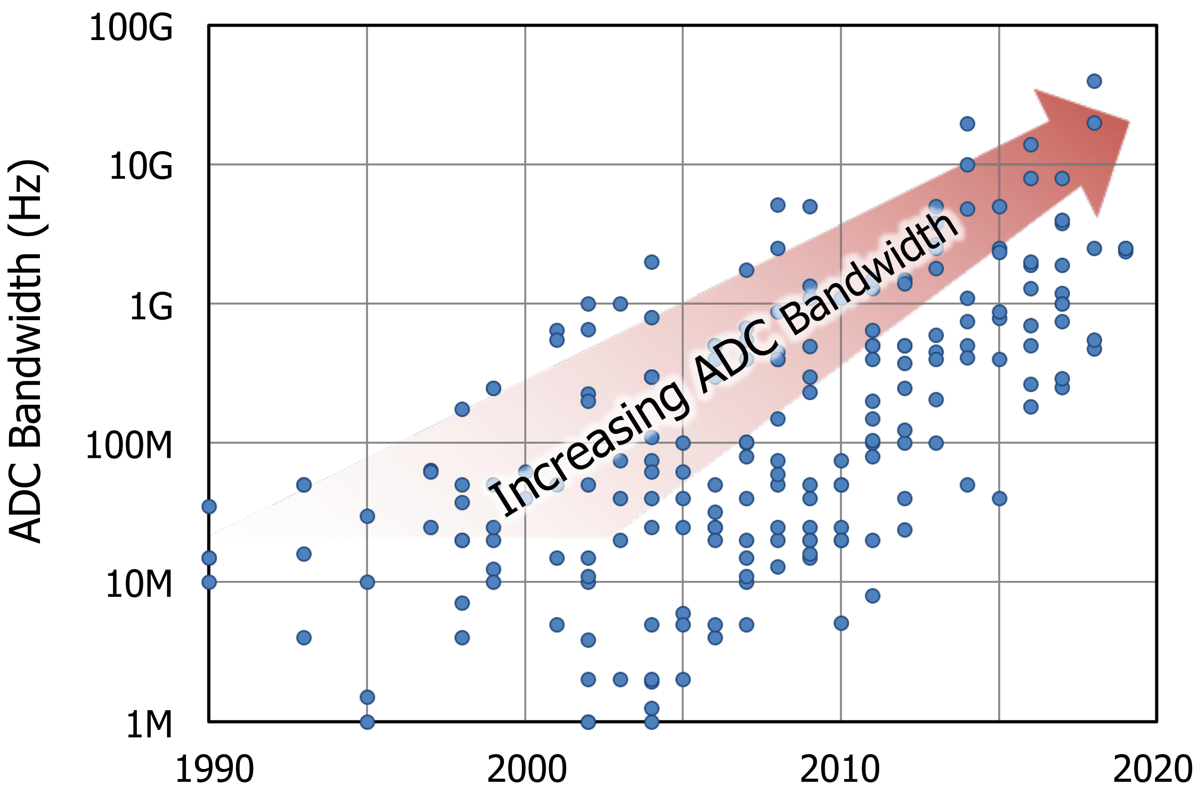
Q: Does DARPA intend to down select the performers at each program phase and what will be the evaluation criteria?

A: Potentially yes, DARPA plans to evaluate the technical progress against the program metrics int the BAA and make program decisions based on the available funding. Among the metrics, **frequency tuning for TA1** and **large time-bandwidth product for TA2** are key goals of the program. The ability of the solution to scale from phase 1 to phase 3 will also be a deciding factor.

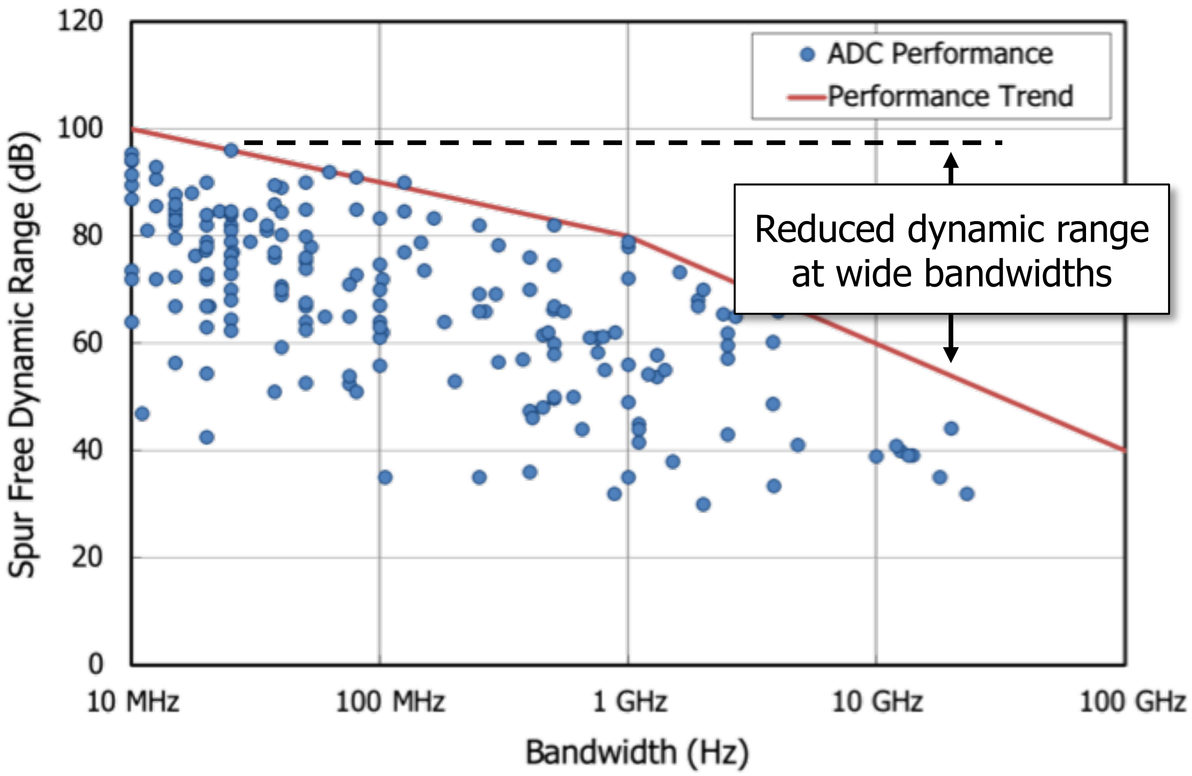
www.darpa.mil

Backup

Wideband ADC Performance Trends

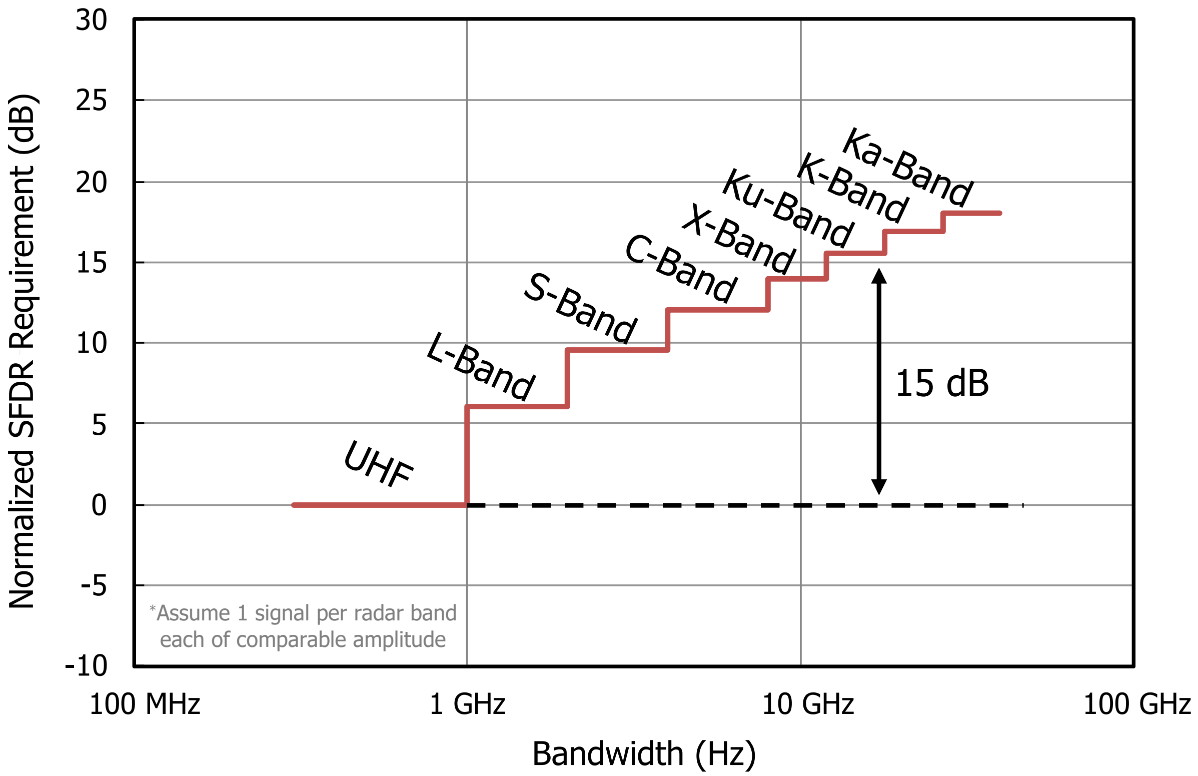


Increasing bandwidth is enabling receivers that can listen simultaneously to multiple bands

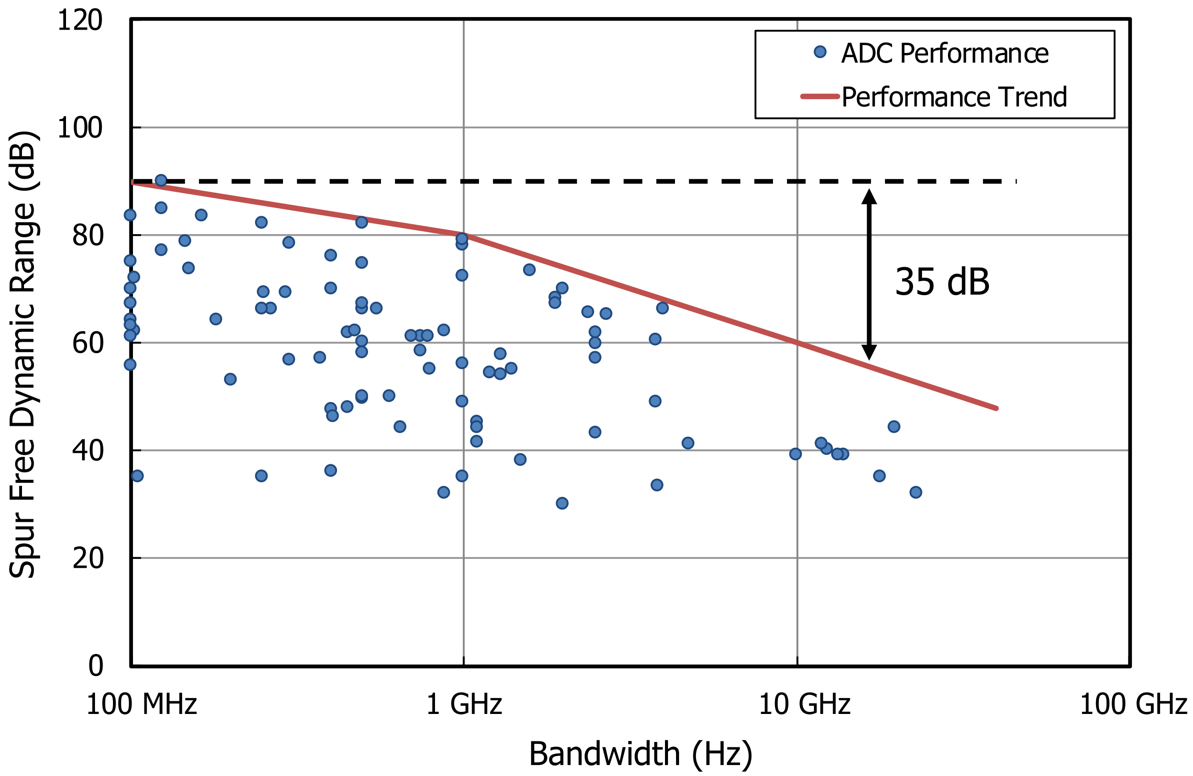


Wideband receivers have less dynamic range than their narrowband counterparts

Increasing Requirement & Decreasing Capability



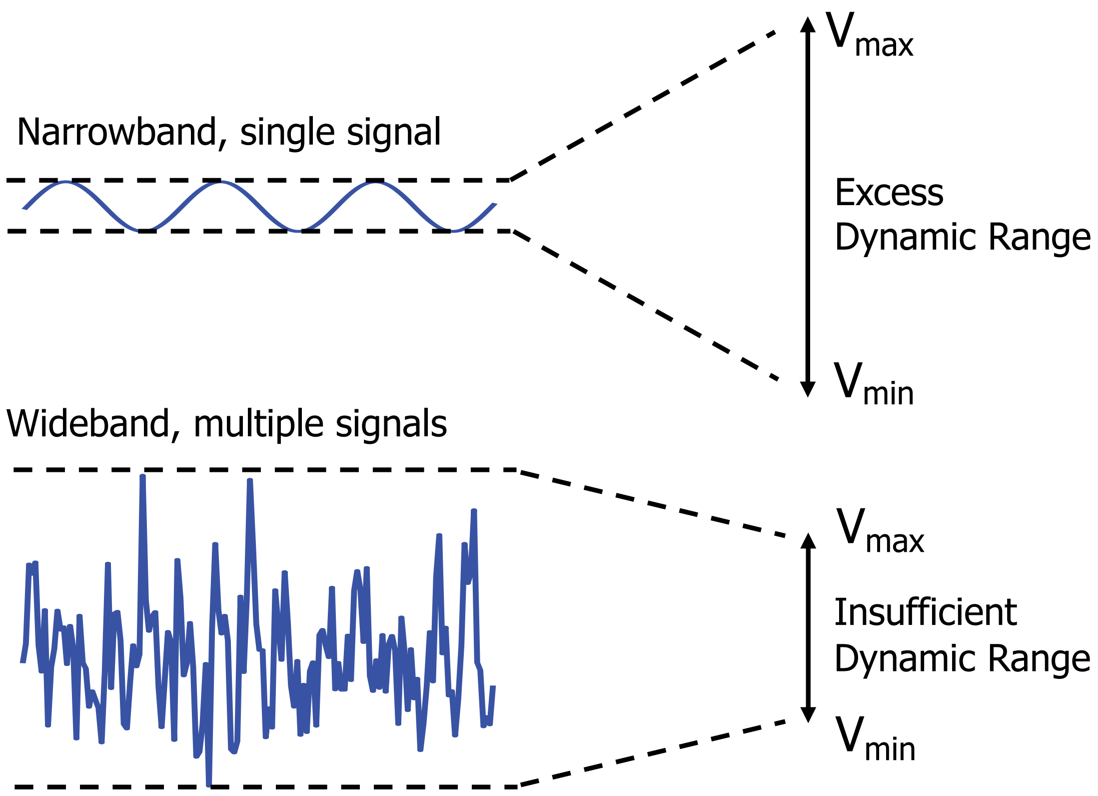
More bandwidth can observe more signals but requires more dynamic range



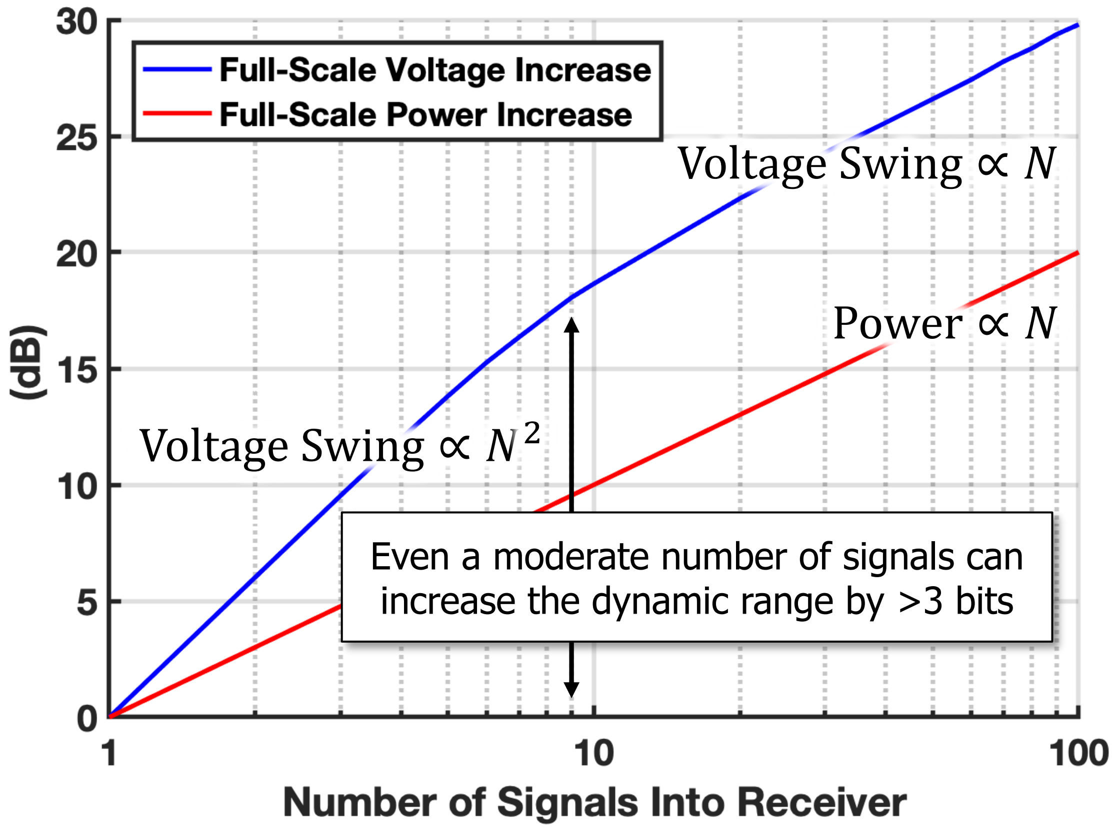
Receiver dynamic range falls off with increasing bandwidth

SFDR – Spur Free Dynamic Range
ADC - Analog to Digital Converter

Wideband Signals Inherently Require More Dynamic Range



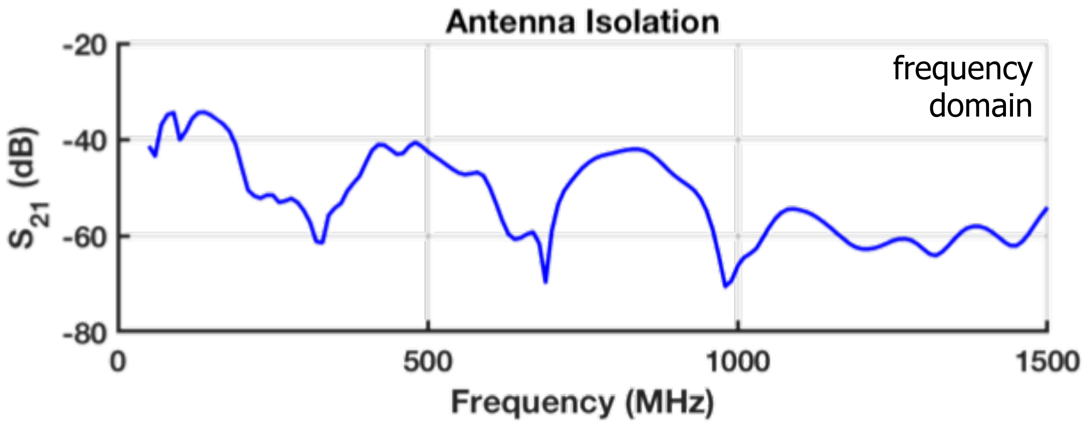
For wide bandwidths, there are more signals to sample and less dynamic range to do so

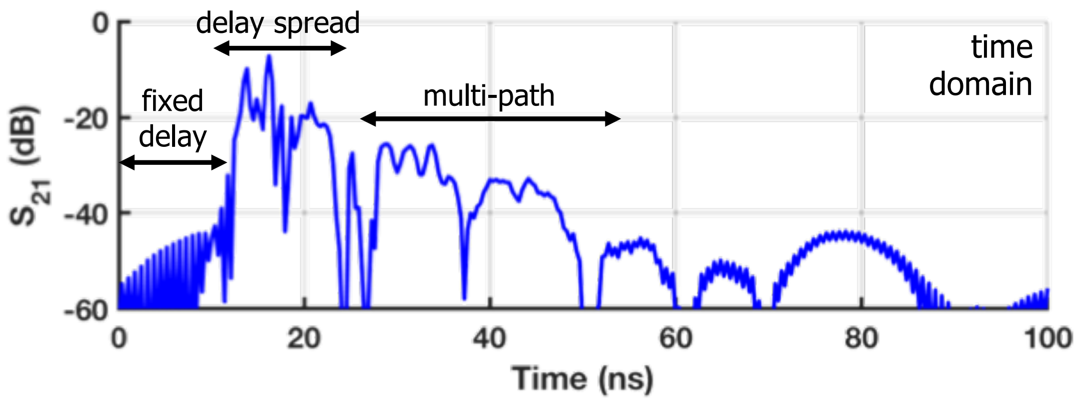


Increasing the number of signals forces a saturation verses sensitivity trade-off

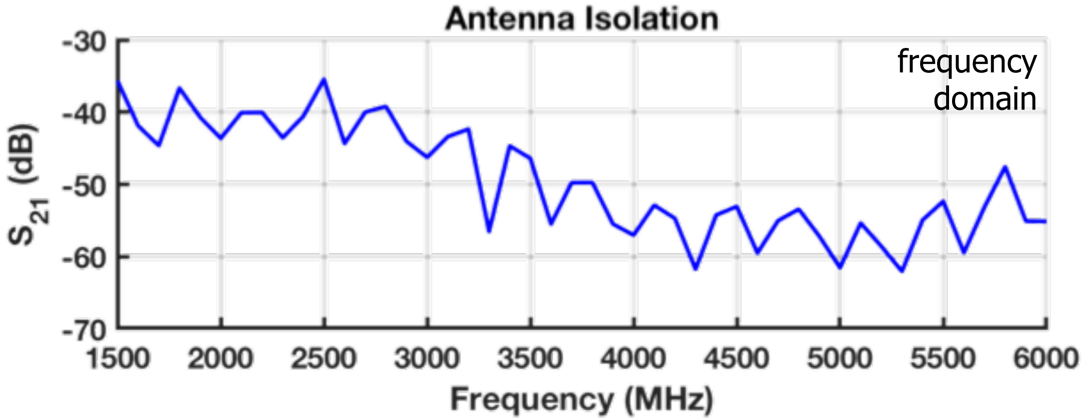
How Much Delay Spread Between Two Wideband Antennas?

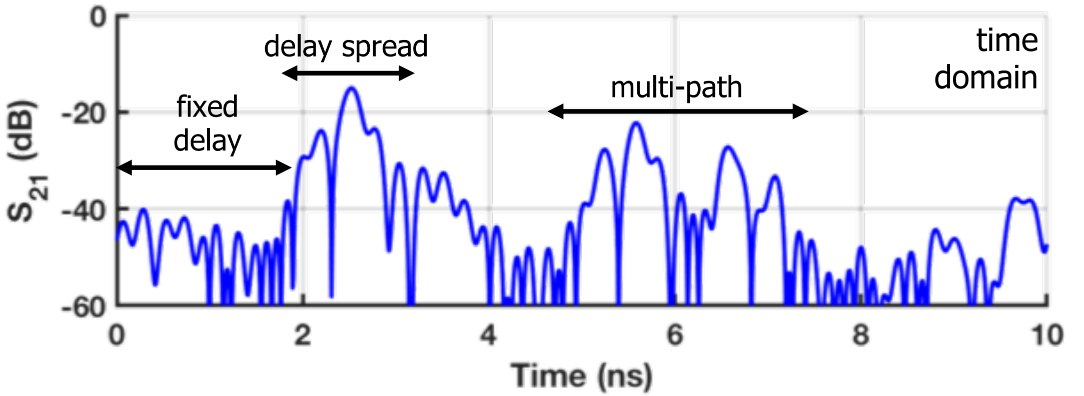
Low-Band (70 MHz – 1500 MHz)





High-Band (1.5 – 6 GHz)

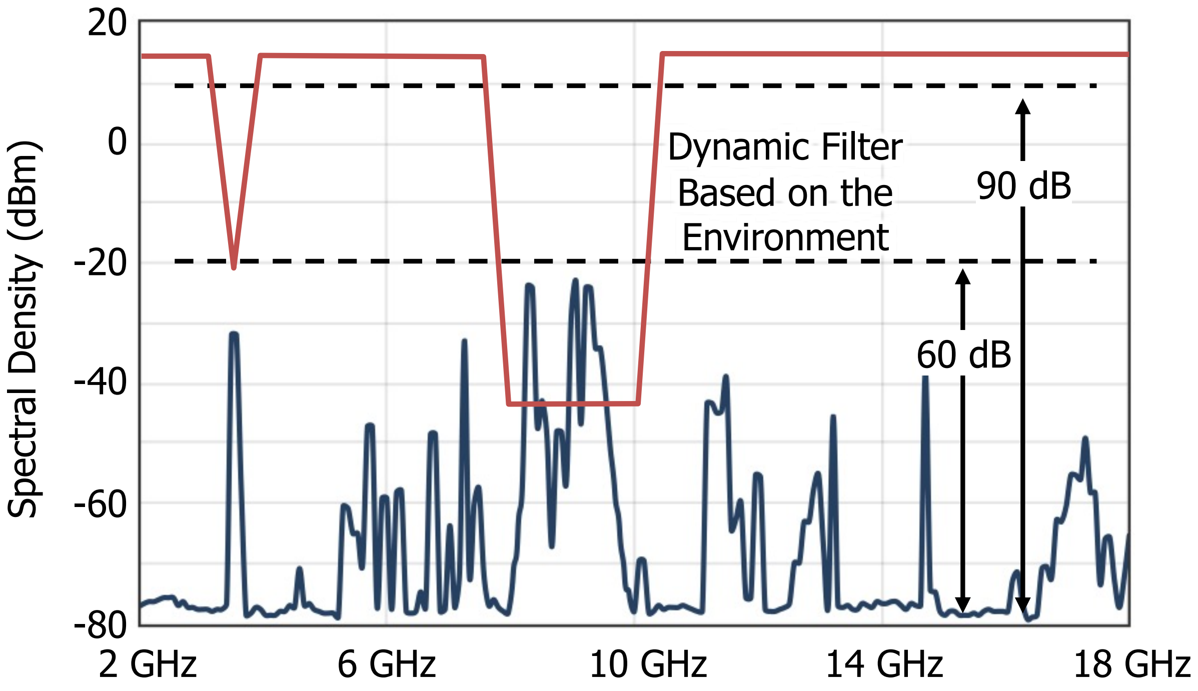




Proportional to lowest frequency and antenna spacing: 10-50 ns range & 10-100 ps resolution

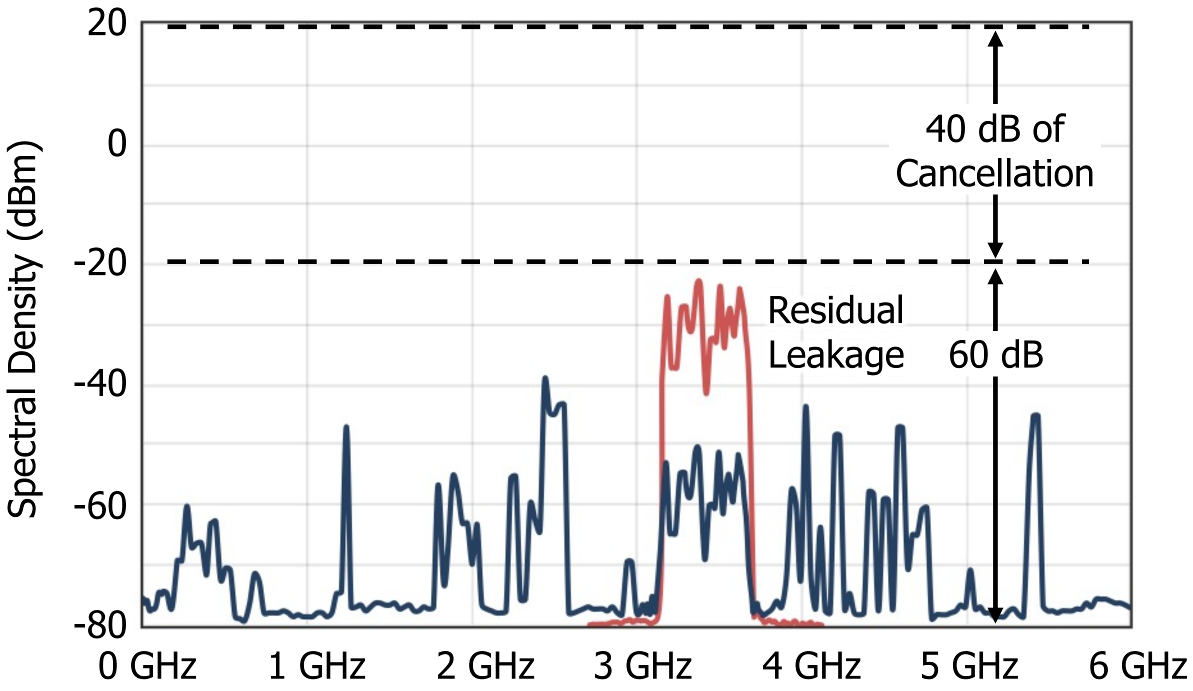
How We Would Like to Protect Receivers in the Future

Wideband Adaptive Filtering



Listen to the environment, adaptively react & selectively attenuate only the large signals

Wideband Signal Cancellation



Estimate the leakage path & adaptively cancel the transmitter leakage